DEFENDING AGAINST BLACK-BOX ADVERSARIAL ATTACKS WITH GRADIENT-FREE TRAINED SIGN ACTIVATION NEURAL NETWORKS

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ABSTRACT

Binary neural networks have been shown to be more adversarially robust than full-precision networks but their improvements are marginal. We propose an ensemble of sign activation neural networks trained with a novel gradient free stochastic coordinate descent algorithm. On the CIFAR10 image benchmark we show that our model has a much higher minimum distortion, as measured by the black box boundary attack method HopSkipJump, than ensembles of binary, full precision, and convolutional neural networks, and than random forests while attaining comparable clean test accuracy. We also show that our ensemble model attains higher accuracy on adversarial examples in text black box attacks across several datasets and is also hard to attack on medical ECG data. In order to explain our model's robustness we turn to non-transferability. We empirically measure the probability that a black box adversary targeting a single network in our ensemble will transfer to other networks and find this to be lowest compared to ensembles of other networks and models. Thus an image requires greater distortion to fool the majority of networks in our ensemble. The non-transferability in our ensemble also makes it a powerful defense to substitute model black box attacks that we show require a much greater distortion than binary and full precision networks to bring our model to zero adversarial accuracy. This property of non-transferability in our ensemble arises naturally from the non-convexity of sign networks and randomization in our training algorithm without any adversarial defense effort.

1 INTRODUCTION

State of the art machine learning algorithms can achieve high accuracies in classification tasks but misclassify minor perturbations in the data known as as adversarial attacks Goodfellow et al. (2014); Papernot et al. (2016b); Kurakin et al. (2016); Carlini & Wagner (2017); Brendel et al. (2017). Adversarial examples have been shown to transfer across models which makes it possible to perform transfer-based (substitute model) black box attacks Papernot et al. (2016a). To counter adversarial attacks many defense methods been proposed with adversarial training being the most popular Szegedy et al. (2013); Tramèr et al. (2017). However this tends to lower accuracy on clean test data that has no perturbations Raghunathan et al. (2019); Zhang et al. (2019) and can still be attacked with better transfer based methods Wu et al. (2020); Xie et al. (2019a); Dong et al. (2019). Many previously proposed defenses have also been shown to be vulnerable Carlini & Wagner (2017); Athalye et al. (2018); Ghiasi et al. (2020) thus leaving adversarial robustness an open problem in machine learning.

A more lethal and practical attack than substitute model training is a boundary based one that requires only the prediction of the model Brendel et al. (2017). These attacks are aimed at finding the minimum distortion to an image such that it will fool a classifier. This is in fact an NP-hard problem for ReLu activated neural networks Katz et al. (2017); Sinha et al. (2017) and tree ensemble classifiers Kantchelian et al. (2016). Even approximating the minimum distortion for ReLu activated neural networks is NP-hard Weng et al. (2018). The HopSkipJump boundary attack Chen et al. (2019) has been shown to give the lowest distortion among such methods.

Binary neural networks that have sign activation and binary weights were originally proposed as lightweight models. These are trained by with gradient descent by approximating the sign activation. Recent work has shown that they tend to be more adversarially robust than full precision networks but the improvements are marginal (see Tables 4 and 5 in Galloway et al. (2017) and Table 8 in Panda et al. (2019)).

In this paper we propose a gradient free stochastic coordinate descent algorithm for training sign activation networks with and without binary weights similar to recent work Xue et al. (2020a;b); Xie et al. (2019b). While our original intention was to study the accuracy of a sign activation network trained directly without any approximation we make an interesting finding on the adversarial robustness of our model. We find that ensembling our model gives a high minimum distortion (as measured by HopSkipJump) compared to full precision, binary, and convolutional neural networks. We explain this phenomena by measuring the transferability between networks in an ensemble.

In summary we make the following observations in our paper:

- Our model has higher minimum distortion than ensembles of full precision and binary neural networks, than random forests that have the advantage of bootstrapping and random feature selection (although only in L_2 and not L_∞ on the data we show in this paper), and than ensembles of convolutional networks that have the advantage of convolutions and several layers.
- Our model's robustness stems from non-transferability of adversarial examples between networks in our ensemble and its robustness increases as we add more networks to the ensemble.
- Substitute model black box attacks require a much greater distortion to bring our model to zero adversarial accuracy compared to ensembles of full precision and binary networks.
- Text classification black box attacks are less effective on our model than on convolutional networks, random forests, and ensembles of full precision and binary networks.
- In a medical diagnosis setting, attacks on ECG data on our model have a higher distortions and are visually distinguishable compared to attacks on ensembles of full precision and convolutional networks, and on random forests.

2 METHODS

2.1 GRADIENT-FREE STOCHASTIC COORDINATE DECENT

Our stochastic coordinate descent is inspired by and similar to recent work Xue et al. (2020a;b); Xie et al. (2019b). In order to understand our training algorithm for a single hidden layer network we first show it for a simple linear classifier. Suppose we are given binary class data $x_i \in R^d$ and $y_i \in \{-1, +1\}$ for $i = 0...n-1$. We wish to determine a linear classifier $w \in R^d, w_0 \in R$ that minimizes the empirical risk for a given loss function $\sum_i L(w, w_0, x_i, y_i)$. At the high level our approach is simple: start with a random solution $w_i \in N(0, 1), w_0 \in N(0, 1)$ for $i = 0...d-1$ and iteratively make incremental changes that improve the risk. In each iteration we select a random set of features (coordinates) from w called F. For each feature $w_i \in F$ we add/subtract a learning rate η and then determine the w_0 that optimizes the risk. We consider all possible values of $w_0 = \frac{w_i^T x_i + w_{i+1}^T x_{i+1}}{2}$ for $i = 0...n-2$ and select the one that minimizes the loss. To avoid local minima in our search we consider a random sample of the training data in each iteration. We set this to 75% of the training data in image and text data experiments and 25% in the ECG data.

We call the above search *stochastic coordinate descent* abbreviated by SCD. In order to train a single hidden layer network we apply SCD to the final node and then a randomly selected hidden node in each iteration of the algorithm. We can train sign activation networks with and without binary weights using our SCD training procedure above. In the case of binary weights we don't need a learning rate. We apply parallelism and several heuristics in practice to speed up the real runtimes. We provide full algorithmic details of our training procedure in the Supplementary Material.

2.2 IMPLEMENTATION, TEST ACCURACY, AND RUNTIME

We implement our training procedure in Python, numpy, and Pytorch Paszke et al. (2019) and make our code freely available from `https://github.com/zero-one-loss/scd_github`. We train three types of sign activation networks with our algorithm: (1) SCD01: 01-loss in the final node, (2) SCDCE: cross-entropy loss in the final node, and (3) SCDCEBNN: cross-entropy in the final node with binary weights throughout the model. Since sign activation is non-convex and our training starts from a different random initialization we run it a 100 times and output the majority vote.

To illustrate our real runtimes and clean test accuracies we compare our models with a single hidden layer of 20 nodes to the equivalent network with sigmoid activation and logistic loss (denoted as MLP) and the binary neural network (denoted as BNN) Courbariaux et al. (2016). We used the MLPClassifier in scikit-learn Pedregosa et al. (2011) to implement MLP and the Larq library Geiger & Team (2020) with the *approx* approximation to the sign activation. This has shown to achieve a higher test accuracy than the original straight through estimator (STE) of the sign activation Liu et al. (2018b).

We perform a 1000 iterations of SCD01 and SCDCE and 10000 of SCDCEBNN. In Table 1 we show the runtimes of a single run of all models on CIFAR10 Krizhevsky (2009) ($32 \times 32 \times 3$, 10K train, 2K test), CelebA facial attributes black hair vs brown hair Liu et al. (2015) ($96 \times 96 \times 3$, 1K train, 1K test), GTSRB street sign recognition 60 vs 120 speed limit signs Stallkamp et al. (2011) ($48 \times 48 \times 3$, 2816 train, 900 test), and ImageNet class 0 vs. 1 Russakovsky et al. (2015) ($256 \times 256 \times 3$, 2580 train, 100 test). Our training runtimes are comparable to gradient descent in MLP and BNN and thus practically usable. We can trivially parallelize training an ensemble by doing multiple runs on CPU and GPU cores at the same time. We also show test accuracies of 100 vote ensembles of all models and find our model accuracies to be comparable to MLP and BNN.

Table 1: Training runtimes of single run in seconds and test accuracies of 100 vote ensembles in parenthesis for binary classification

	SCD01	**SCDCE**	**SCDCEBNN**	**MLP**	**BNN**
CIFAR10	64 (87%)	56 (88%)	422 (87%)	13 (90%)	106 (83%)
CelebA	20 (79%)	18 (81%)	111 (72%)	41 (78%)	32 (76%)
GTSRB	22 (97%)	22 (97%)	92 (98%)	8 (99%)	42 (96%)
ImageNet	77 (72%)	54 (73%)	338 (71%)	115 (72%)	78 (66%)

3 RESULTS

Going forward we compare the adversarial robustness of ensembles of our three models SCD01, SCDCE, and SCDCEBNN, their full precision and binary gradient descent trained equivalent counterparts MLP and BNN, two convolutional neural networks: LeNet LeCun et al. (1998) and ResNet50 He et al. (2016), and random forests Breiman (2001) (denoted as RF). For each model we use the majority vote output of 100 votes each with different initial parameters except for ResNet50 where we use 10 votes. In random forest we use an ensemble of 100 trees.

We use a single hidden layer of 20 nodes in our three models and in MLP and BNN throughout the paper. The convolutional networks and random forest are not a fair comparison to our model since it has fewer parameters and does not perform bootstrapping or random feature selection as random forest. We include them nevertheless since convolutional neural networks serve as state of the art references and random forest serves as an alternative ensemble method.

3.1 ADVERSARIAL DISTORTION ON IMAGE DATA

The minimum distortion required to make a datapoint adversarial is an indicator of a model's adversarial and even corruption/general robustness Gilmer et al. (2019). We consider 10 randomly

selected datapoints from the CIFAR10 benchmark Krizhevsky (2009) and report their minimal adversarial distortion as given by HopSkipJump Chen et al. (2019). Compared to other boundary attack methods Brendel et al. (2017) it is known to give the best estimate of a datapoint's minimum adversarial distortion.

We use the HopSkipJump implementation in the IBM Adversarial Robustness Toolkit (ART) Nicolae et al. (2018) In order to obtain as accurate an estimate as possible we run HopSkipJump 10 times each with an initial pool size of 1000 random datapoints and maximum iterations of 100 and report the minimum value. For a single datapoint this typically takes several hours to finish and thus we are able to report the distortion of only 10 random points in this study.

In Table 2 first row we show the clean test accuracy of all models on CIFAR10 class 0 vs. 1. The convolutional networks LeNet and ResNet50 have higher accuracies since they have the advantage of convolutions. However, our sign activation trained models have the highest adversarial distortion with the binary weights cross-entropy variant as the winner. All other neural networks lag far behind and have distortion even lower than random forest. Even though BNN also has sign activations its distortions are similar to MLP possibly due to its approximation of the sign activation and gradient descent search. If we use the the straight through estimator and swish approximations Darabi et al. (2018) the distortions remain similar to what we report here.

Table 2: Minimum L_2 adversarial distortion of 10 random test images from CIFAR10 class 0 vs. 1

	SCD01	**SCDCE**	**SCDCEBNN**	**MLP**	**BNN**	**ResNet50**	**LeNet**	**RF**
Clean acc	87	88	88	90	83	98	96	88
Image 0	2.21	2.65	3.3	0.44	0.82	0.57	1.43	0.8
Image 1	0.52	1.6	1.67	0.64	0.78	0.65	0.45	0.06
Image 2	2.42	3.41	3.58	0.75	0.78	0.98	2.47	0.71
Image 3	4	3.84	3.3	0.48	0.31	0.7	1.05	2.24
Image 4	4.56	4.14	3.44	1.15	0.82	0.54	0.58	3.04
Image 5	2.86	1.85	1.27	0.84	0.17	0.35	0.24	0.44
Image 6	2.47	2.35	3.77	0.91	0.73	0.38	2.61	1.01
Image 7	1	2.38	2.91	0.39	0.94	0.96	2.8	1.71
Image 8	3.94	4.35	4.35	0.74	0.71	1.11	2.84	1.87
Image 9	8	7.07	8.37	1.39	1.5	1.34	2.86	7.2
Average	3.198	3.364	3.596	0.773	0.756	0.758	1.733	1.908

In Table 3 we compare the L_∞ distortions and make similar observations as above except that random forest has the highest L_∞ distortion. This suggests that in order for an image to fool our model changes have to made in many pixels whereas in random forest a larger change in fewer pixels is sufficient.

3.2 Transferability within ensembles and effect of ensemble size

To understand the above phenomena we estimate the probability that an adversarial example targeting a single model in the ensemble will also be adversarial to other models in the ensemble. We can estimate this by first performing a HopSkipJump attack on each model in the ensemble separately. Let x'_i be the adversary obtained by targeting model m_i in the ensemble. Let k_i be the number of models in the ensemble that are also misclassified by the adversary x'_i (thus transferable). We sum k_i for $i = 0...n-1$ and divide by 9900 which is the maximum value of this sum (obtained when the adversary attacks all models in the ensemble excluding the target of course).

We average this probability for Images 0 through 7 for each method. In Table 4 we see that this probability is lowest for our models and highest for MLP and BNN. The fact that this probability is very low for our models indicates that for several of the networks in our ensemble the adversary targeting a fixed network does not transfer to other ones. The low transferability of our models indicates that a greater distortion is required for an image to be adversarial.

Table 3: Minimum L_∞ adversarial distortion of 10 random test images from CIFAR10 class 0 vs. 1

	SCD01	**SCDCE**	**SCDCEBNN**	**MLP**	**BNN**	**ResNet50**	**LeNet**	**RF**
Image 0	0.16	0.18	0.22	0.03	0.04	0.085	0.1	0.19
Image 1	0.041	0.1	0.11	0.043	0.03	0.06	0.03	0.04
Image 2	0.15	0.2	0.24	0.06	0.03	0.12	0.17	0.19
Image 3	0.25	0.24	0.22	0.036	0.01	0.08	0.08	0.45
Image 4	0.28	0.28	0.24	0.09	0.03	0.06	0.04	0.37
Image 5	0.19	0.12	0.08	0.06	0.01	0.03	0.02	0.16
Image 6	0.17	0.17	0.25	0.07	0.04	0.05	0.2	0.61
Image 7	0.09	0.16	0.18	0.03	0.04	0.12	0.21	0.42
Image 8	0.27	0.3	0.28	0.05	0.03	0.13	0.23	0.58
Image 9	0.52	0.52	0.54	0.1	0.06	0.18	0.23	0.73
Average	0.2121	0.227	0.236	0.0569	0.032	0.0915	0.131	0.374

Table 4: Estimated probability that an adversarial image targeting a single model in the ensemble (of 100 models) will transfer to other models.

	SCD01	**SCDCE**	**SCDCEBNN**	**MLP**	**BNN**	**ResNet50**	**LeNet**	**RF**
Prob	.006	.004	.002	.39	.2	.02	.01	.07

In fact as we see in Figure 1 the robustness of our models increases as we increase the ensemble size to a much larger degree than ensembles of MLP and BNN, and than RF. We use ensemble sizes of 100 in this study but the figure suggests that increasing our ensemble size is likely to further increase robustness.

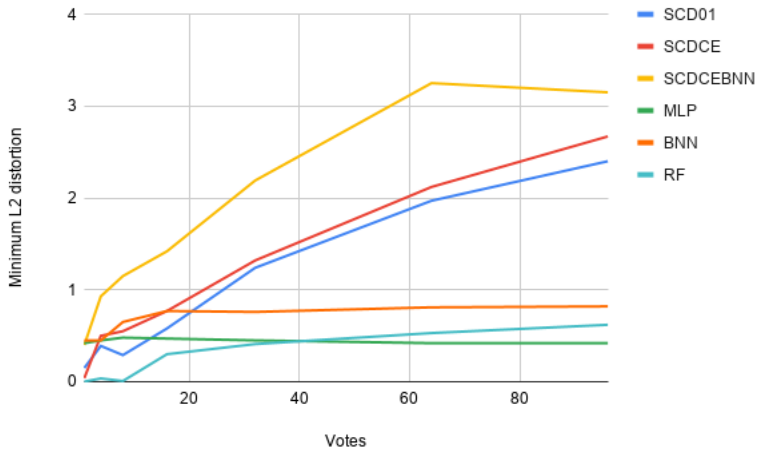

Figure 1: Minimum L_2 image distortion as a function of ensemble size

3.3 Substitute model black-box attacks

Our model's high distortion in CIFAR10 is reflected in substitute model black box attacks on this dataset Papernot et al. (2016a). We train a two hidden layer neural network each with 200 nodes as the substitute using the standard adversarial augmented algorithm Papernot et al. (2017) (described

fully in the Supplementary Material). In Figure 2 we that our models require a much higher distortion than their gradient descent trained equivalents MLP and BNN in order to reach zero percent adversarial accuracy. We also see that all models attacked with random Gaussian noise of the same distortion added to the test examples are barely affected thus showing the effectiveness of the black box adversarial examples.

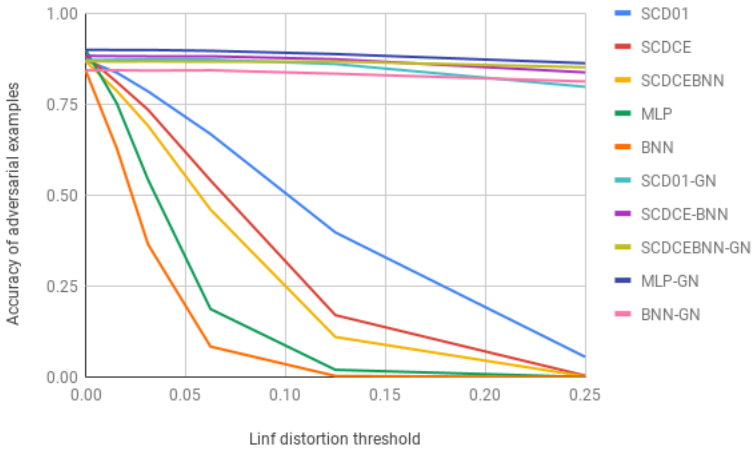

Figure 2: Accuracy of adversarial examples and test data with Gaussian noise (denoted as -GN for each model) for various distortion thresholds on CIFAR10. The substitute model adversarial examples are far more effective than random noise. At distortion 0.125 both MLP and BNN have near 0% accuracy whereas SCD01 has 40%.

3.4 TEXT BLACK-BOX ATTACKS

The TextFooler Jin et al. (2019) method is designed to find syntactically and semantically similar adversarial documents by replacing important words with similar ones until the document is misclassified. We apply this to all ensemble models on four document classification datasets: Internet Movie Database (25K train, 25K test, mean words per document: 215) and Yelp (560K train, 38K test, mean words per document: 152) positive and negative reviews (IMDB and Yelp), sentence classification of positive and negative sentiments (9K train, 1K test, mean words per document: 20, denoted as MR), and sentence-level classification of news items in World and Sports categories (120K train, 7.6K test, mean words per document: 43, denoted as AG) Jin et al. (2019).

WordCNN stacks word vectors Pennington et al. (2014) of each word in a document into a matrix to treat it as 2D image Kim (2014). In the other models that take feature vectors as inputs we consider the averaged word vector of all words in a document Lilleberg et al. (2015). For all models we use 200 dimensional Glove word embeddings pre-trained on 6 billion tokens from Wikipedia and Gigawords Pennington et al. (2014). This gives a lower clean test accuracy than WordCNN but still above an acceptable level in practice.

In Table 5 we see that ensembles of our models give the highest adversarial accuracy on all four datasets and require the greatest number of queries. If a smaller limit was placed on the allowed queries (for example imposed by the system being attacked) we can expect a higher adversarial accuracy for our models. Here we show ensembles of 8 votes for each model. If we increase the ensemble size to 100 we find the adversarial accuracy of our models, BNN, and RF slightly drop but their relative difference remains the same.

3.5 ECG BLACK-BOX ATTACKS

ECG time-series data is increasingly being used in automatic diagnosis by machine learning systems Ribeiro et al. (2020). Tailored adversarial attacks have recently been proposed Han et al. (2020); Chen et al. (2020) but HopSkipJump can also be used to produce adversarial ECG examples. To

Table 5: Accuracy of clean and TextFooler black-box adversarial examples denoted by Cl and Adv respectively. Also shown are the number of queries made by the attacker denoted as Que. We round accuracies and queries to the nearest integer.

	IMDB			**Yelp**			**MR**			**AG**		
	Cl	**Adv**	**Que**	**Cl**	**Adv**	**Que**	**Cl**	**Adv**	**Que**	**Cl**	**Adv**	**Que**
SCD01	82	51	3279	85	54	1908	74	14	186	99	93	672
SCDCE	84.8	52.4	3255	86	56.7	1903	75.8	16.7	189	99	94.5	687
CNN	89.2	0	524	94	1.1	492	78	2.8	123	96.5	49.1	258
MLP	85	0	686	87.3	. 2	500	75	2.3	123	99	51.4	366
BNN	83.8	21.5	2301	85	32.3	1622	73.2	5.8	150	99.1	75.6	564
RF	76.7	11	1823	77.7	7.5	935	68.1	2.1	115	96.7	72.2	532

illustrate this and evaluate our model's robustness on this data we consider the PTB Diagnostic ECG dataset Bousseljot et al. (1995); Goldberger et al. (2000) available from this URL `https://www.kaggle.com/shayanfazeli/heartbeat`. We randomly split this dataset into an 80:20 train test split.

We train 100-model ensembles of SCD01, SCDCE, and MLP. We also train an ensemble of 10 convolutional neural networks (CNN) with 1D convolutional kernels and random forest (RF) with 100 trees. Each of our CNNs has the following structure: 64 1x16 Conv1D kernels $\rightarrow$ MaxPool 1x4 $\rightarrow$ 128 1x16 Conv1D kernels $\rightarrow$ MaxPool 1x4 $\rightarrow$ 256 1x16 Conv1D kernels $\rightarrow$ MaxPool 1x2 $\rightarrow$ FullyConnected $\rightarrow$ Output. In Table 6 we see the clean test accuracy of our model is slightly lower than gradient-descent trained models and random forest. We picked 37 random datapoints from the test and attacked all models on these points. We attack each point 10 times and report the minimum with the same parameters as we did in our CIFAR10 attacks described above.

In Table 6 second row we show the average min L_2 distortion and find SCD01 to have the highest one. The L_2 difference between SCD01 and the next best RF (after SCDCE) turns out to be statistically significant with a p-value of .008. As we saw earlier in CIFAR10 the L_∞ distortion of random forest is higher but not statistically significant with a p-value of 0.07.

Table 6: Clean test accuracy and minimum L_2 and L_∞ adversarial distortion on the PTB Diagnostic ECG dataset

	SCD01	**SCDCE**	**MLP**	**CNN**	**RF**
Clean acc	91.1	93.3	96.1	99.6	97.6
Average min L_2 distortion	.18	.14	.08	.1	.14
Average min L_∞ distortion	.08	.06	.03	.04	.11

In Figure 3 we visualize an original ECG sample and its adversarial versions targeting SCD01, CNN, and RF. The SCD01 adversary is rigid and has many more bumps compared to the CNN and RF adversaries and is thus likely to be detected by an observer or a system that checks for smoothness (that we expect to see as in the original sample).

3.6 Discussion

Using ensembles of neural networks and promoting diverse ensembles has been previously proposed as a defense against adversarial attacks. Studies using ensembles with different initializations (like we do), bootstrapping, and Gaussian noise have shown robustness but only in the white box setting Strauss et al. (2017) (which is somewhat unrealistic since it assumes the attacker has full knowledge of the model and its parameters). Other studies combine the loss of all models in the classifier and add a regularizer that promotes diversity.

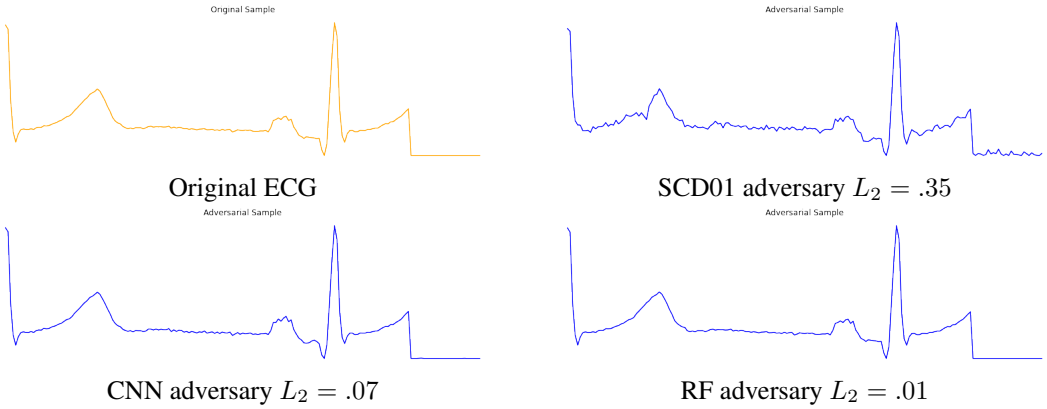

Figure 3: Original and adversarial ECG examples

For example we could try to maximize the angle between gradients of models in the ensemble Kariyappa & Qureshi (2019) to make them *misaligned*. In their diversity training they use a Gaussian noise augmented dataset which raises concerns about the effectiveness of their method since augmentation alone has been shown to be effective in ensemble training Strauss et al. (2017). Another study maximizes diversity between classes Pang et al. (2019) and thus does not apply to our work here that focuses on binary classes only. Even for multiple classes their method is computationally expensive as it uses a joint loss function. Other methods inject noise to models in the ensemble Liu et al. (2018a) but their evaluation is only in the white box setting. Various measures for ensemble diversity have been previously proposed for deep networks Liu et al. (2019) and evaluated in the white-box setting.

We can apply all of the above diversity training methods to our ensemble of sign networks. Our work, however, is not explicitly aimed at enhancing diversity. As we show it is naturally diverse and we conjecture this is due to the non-convexity of sign activation and our randomized training method. Even sigmoid activation networks have a non-convex search space but we can imagine that sign activation gives a greater degree of freedom. This can easily be seen in the case of a linear classifier with logistic or hinge loss vs. 01 loss Xue et al. (2020b).

Our model accuracy is not the same as convolutional networks understandably due to lack of convolutions in our networks. But they are close to sigmoid activated networks and random forests, and better than binary neural networks in most cases. It is possible to extend our training procedure to allow for convolutions and this may increase accuracy making our model comparable to convolutional networks and much more robust.

It is hard to make a general claim of robustness with only 10 images from CIFAR10. We would need to show more images from CIFAR10 and other image benchmarks as well but our preliminary experiments suggest higher distortion on other image data as well. For example on a single random test datapoint in CelebA our SCDCE ensemble has minimum L_2 distortion of 8.6 while the next best LeNet ensemble is 3.3. Due to computational limitations we are unable to show more image data here but instead we take another route to show generality of our results. We show that our model is robust even to text classification black box attacks and on ECG data attacks. Both of these are outside the domain of images and our model's robustness there suggests a greater generalization. Future work entails extending our training to sign activated convolutions and multi-class networks.

3.7 Conclusion

We show that our ensemble of gradient-free sign activation networks have a higher image adversarial distortion than ensembles of several other networks and random forests on 10 random images in CIFAR10. We then give a transferability based argument to support this result and show robustness on text document and ECG data classification.

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